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PLATE MANIPULATORS

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ABSTRACT This article reviews the course of the development of research relating to flat plate type turbulence control devices or plate manipulators. It sets up, on the foundation of our own flow visualizations or displays, a proposal for a new drag reduction mechanism. It refines designs, and, in conjunction with that, achieves relatively good drag reduction results.

KEY TERMS Plate Manipulator, Turbulence Structure, Drag Reduction

#### FORWARD

Objects which are moving in a fluid cannot escape having exerted on them drag forces supplied by the fluid. In addition to this, it is precisely due to these fluid drag forces reducing the capabilities of aircraft that aircraft speeds are blocked from being increased another increment. Because this is the case, research relating to the reduction of aircraft drag forces forms one of the most ardent focal points for aerodynamics scholars of various countries. Among the drag forces which are exerted on aircraft, skin friction or surface drag forces are taken to be the greatest, making up approximately 50%. Moreover, among surface drag forces, turbulence drag forces are also taken to be the main ones. Because this is the case, how to control turbulence flows to reduce surface drag forces is obviously extremely important. Previously, turbulence flow control was mainly through forms changing boundary layer velocities or fluid viscosities near wall surfaces. However, it has only been in the last ten years that directly carrying out control of the internal structure of turbulent flow boundary layers in order to arrive at drag reduction targets has received serious attention, for

example, wall surface channeling pattern methods, flat plate type turbulence flow control devices, and so on<sup>(1)</sup>.

## I. PLATE MANIPULATORS

Regarded as the most exciting at present, plate type turbulence control devices (some are known as "large vortex break up devices") have attracted numerous scholars from such nations as India, the U.S., the U.K., Canada, Sweden, Japan, China, and Germany to carry out research on them. Going through ceaseless improvements, flat plate control devices have been made into a very thin plate or wing type system. The chord length is slightly larger than the boundary layer thickness. It is fixed to the outer layer of turbulent flow boundary layers (that is,  $l = 1 \sim 1.5 \delta$ ,  $h = 0.6 \sim 0.8 \delta$ ). In conjunction with this, it is parallel to the oncoming flow. Single plate control devices are capable of making local wall surface drag forces down the flow drop over 10%. Moreover, the effective zone of drag reduction reaches a high of  $150 \delta$ . However, due to system drag forces associated with the plates themselves, we are still some distance from net drag reduction. At the present time, we have still not seen reports on using single plates to achieve net drag reduction.

As far as opting for the use of plate type turbulent flow control devices is concerned, the first benefits from net drag reduction were gotten by Plesniak and Nagib<sup>(2)</sup>. They opted for the use of control devices with two single plates front and back ( $l_1 = l_2 = 2 \delta$ ,  $h = 0.4 \sim 0.8 \delta$ ,  $S = 11 \sim 14 \delta$ ) and got net drag reduction benefits as high as 20%<sup>(2)</sup>. Although other research teams have net drag reduction benefits under the same conditions of only 4~8%, even so, this makes research on the control systems in

question one with even broader future prospects. The Swedish spaceflight agency took this type of system and installed it on a full scale flight craft with  $M=0.9$ . They also obtained net benefits.

## II. DISCUSSION OF DRAG REDUCTION MECHANISMS

Despite the fact that it has perhaps made people feel surprise or even regret, the speedy development of these types of turbulent flow control methods has certainly not as yet given a clarifying answer with regard to drag reduction mechanisms. People are still in dispute. The final result is that net drag reduction benefits have been realized from both control device applications fixed on walls and their wake effects. Narasimha, by contrast, believes that net drag reduction can only be obtained within a limited area. In areas sufficiently far down the flow from control devices, it is necessary that the total drag forces be maintained invariable. That is to say that, sufficiently far down the flow, drag forces will have a transition, causing the total drag forces to be the same as when control has not been applied. Making an overall synthesis of the currently existing drag reduction mechanisms, they can be roughly divided into two types, that is, the fixed wall effects of control devices and wake effects. Moreover, within the two types of effects, the influencing parameters are also matters on which each holds his own views.

a. As far as speed losses associated with flat plate control device locations are concerned, flows go through an amount of looping effect and rush downward toward wall surfaces.

b. Wake vortices and the results within boundary layers mutually effect each other. In conjunction with this, energy is acquired from vortices in the direction of vortical development associated with relatively large scale flows in that direction, causing attenuation up to and

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including disappearance. Therefore, there is a reduction in the momentum transmission associated with wall surfaces<sup>(3)</sup>.

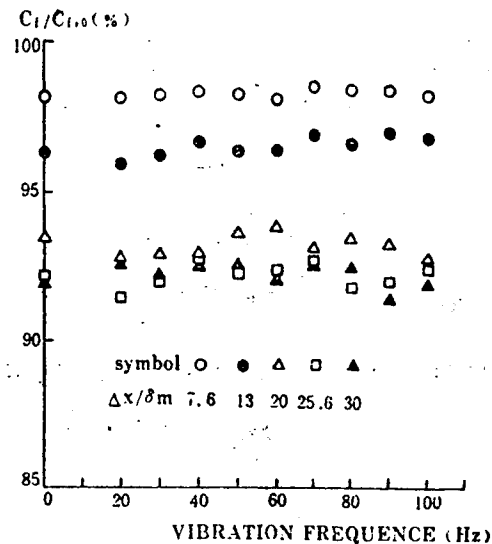
c. As far as the relationships between the inner and outer layers into which wake vortex paths are divided are concerned, they make it difficult for the irrotational fluids of the outer layers to penetrate into the inner layers. They also avoid the pulsations of the outer layers, for example, influences on inner layers such as background turbulence flows, and so on.

d. With regard to the breaking up of large scale outer layer vortices, this means a reduction in the production and transmission of turbulent flow energy.

e. Restrictions of y direction velocities and their pulsations.

f. Flat plates fixed to walls have a strong inhibiting effect on vortical rotations in the direction of development of hairpin structures<sup>(4)</sup>.

a-c are wake drag reduction mechanisms. Narasimha combines the currently existing wake effects (that is, main wall surface drag force drops which lead to the creation of speed losses). It was discovered that, with this the case, the amount of drag reduction obtained is much smaller than actual needs. Furthermore, even less can one use momentum losses in order to produce drag reduction (mechanism a). Moreover, it is not very possible that one will obtain net benefits. We opted for the use of calculations in a turbulent flow two equation model to verify this point<sup>(5)</sup>. Because of this, plate turbulent flow control devices, to obtain net benefits, must necessarily possess other types of factors in giving rise to



the effects. Trailing edges of control devices will produce wake vortices. If, due to the mutual effects of these wake vortices and other structures inside boundary layers, they lead to wall surface drag reductions, then, opting for the use of different methods to produce similar wake vortices should have similar drag reduction results. However, opting for the use of fine columns in order to control the effects of turbulent flow boundary layers will still be much different from plate type control devices. A different experiment clearly shows that, when plate type control devices and oncoming flows have tiny positive angles of attack, drag reduction results are almost identical to those when there is no angle of attack ( $\alpha < +3^\circ$ ). This means that, when there is an angle of attack, strengthened wake vortices most certainly do not cause wall drag forces to drop even more. In our tests, opting for the use of up and down vibration methods to change wake vortex strengths and scales most



certainly did not cause wall surface drag forces to exhibit greater changes (Fig.1). This is also to say that mechanism b cannot possibly be a primary factor. In mechanism c, it is believed that there is a connection between the inner and outer layers that wake vortices are isolated into. In this regard, the correlation measurements of references (6,7) clearly say that, closely following control, the inner and outer layer connection associated with trailing edges is weakest and subsequently returns to normal very rapidly. If one posits the connection between the inner and outer layers into which wakes isolate out, then, following the very rapid dispersion of wall surfaces and outer layers, approximately  $30 \delta$  down the flow from the plates, the dispersion goes to a single integral boundary layer. The functions of this type of isolated inner and outer layers will be lost. In actuality, a good number of experiments all demonstrate that drag force reduction areas are approximately within  $100-150 \delta$ , even extending to larger areas. Savill and Mumford's<sup>(3)</sup> smoke flows display that two plate upper and lower overlap and forward and trailing arrangements abreast will produce strengthened wake isolation. The estimates were that these two types of systems should possess the same type of net drag reduction effects. In fact, the former still did not achieve the predicted effects. This also makes clear that mechanism c, in wall surface or skin drag reduction, does not play a leading role.

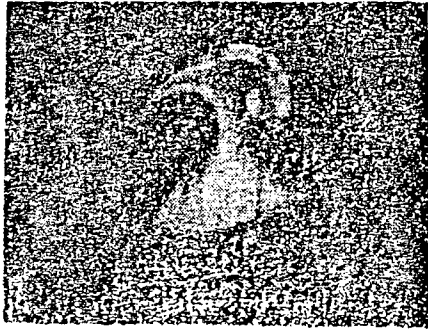
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One group of scholars lays particular stress on the decisive role of the fixed wall effects of plate type control devices or manipulators on drag reduction. However, with regard to these types of effects, there are still different points of view as to which physical processes they, in the final analysis, influence. Although Corke and others

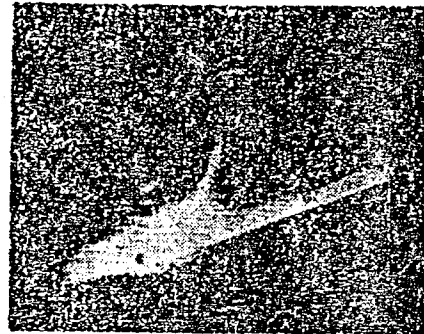
have observed the phenomena associated with the break up of large scale structures (smoke thread displays), the conditioned samplings of Blackwelder<sup>(6)</sup>, Shi<sup>(7)</sup>, and others also verify the results of large vortices being attenuated. However, it is very difficult to imagine this attenuation of large vortices being a direct effect of fixed or solid walls. The reason for this is that, using control devices with chord lengths of approximately  $\delta$ , it is necessary to have relatively large inhibiting effects on the large scale vortices of outer layers, which are slowly rolling over and over, and that is not very possible. Later, Corke and others also recognized that large vortex break up is an indirect result. If one reduces velocity pulsations associated with direction  $y$ , large vortices have a chance of being inhibited or attenuated. However, the experiments in reference (3) clearly show that flat plates also draw in large scale velocity pulsations in the  $y$  direction. It is recognized that this cannot possibly become a primary factor in drag reduction. Blackwelder and Chang<sup>(6)</sup>, by contrast, believe that limiting high speed irrotational fluids scouring against or eroding wall surfaces possesses key effects: (1) it reduces irrotational fluids being drawn into boundary layers, that is, it retards the growth of boundary layers; (2) after the processes of seeping through and mixing at control device locations is attenuated, reciprocal effects of inner and outer layers weaken; (3) burst strengths and their processes, due to wall surface scouring or erosion, are reduced in speed and attenuate. Starting from this vantage point, it is possible to know that plate type control devices or manipulators are best positioned on a wave valley between large scale vortices.  $h = 0.4 \delta$  is most suitable. The reason for this is that, at this location, irrotational fluids are most easily drawn into

boundary layers. However, experiments clearly show that it is still plates when  $h = 0.6 \sim 0.8 \delta$  that have optimum drag reduction results.

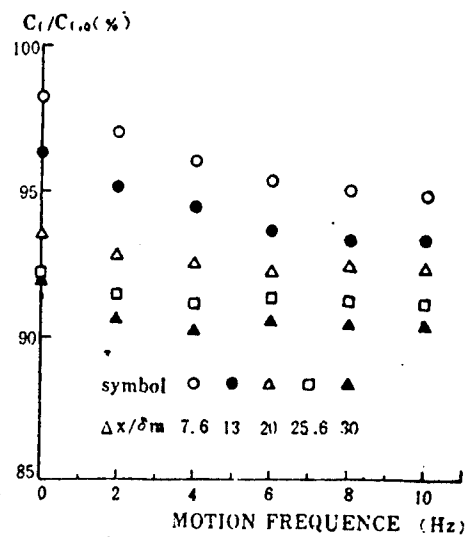
Mechanism f stresses the strong inhibiting effects flat plate fixed walls exert on vortex heads in the direction of the development of hairpin structures. This phenomenon was first observed in flow field displays inside a smoke wind tunnel<sup>(4)</sup>. In order to avoid opening up a turbulent flow background which is disordered and complex, we opted for the use of the heat pulse wire method which is capable of successfully taking ordered turbulent flow structures and transplanting them into laminar flow boundary layers. Moreover, there are almost no added effects on coherent structures. Fig. 2a and 2b respectively are hairpin structures before and after plate control or manipulation. When hairpin structures flow through plate control devices or manipulators, the hairpin vortex heads are, first of all, strongly inhibited. After that, they go through autoinduction effects, causing the entire hairpin structure to be attenuated. That is to say that the strength of hairpin structure vortices in the direction of flow weaken. Moreover, because of this, the low speed fluid belts which are produced are cleaned up and turned relatively stable, not resembling that original type, drifting from place to place along the direction of development. This means that the turbulent flow energy produced is lessened. Another key phenomenon is, after vortical heads have been inhibited, a very great drop in the occurrence frequency of large vortices produced by mutual induction. For example, in reference (4) experiments, when single plates were used, the frequency of large vortex production fell to half its original rate. This and the phenomenon of low speed belts



(a)



(b)



tending toward stability are in conformity. The reason for this is that they both signify a reduction in the production

of turbulent flows, in the end, causing wall surface or skin drag forces to drop. In order to verify the results of the above flow movement displays, we maintained the distance between two hot lines invariable. Moreover, we changed the hairpin structure which was drawn up with a measurement correlation coefficient  $R > 0.3$  for the included angle between the wall surface or skin and probe connection lines, and it was discovered that plate control devices or manipulators definitely exert a strong limitation on the probability of producing hairpin structures. We also used linear position flow theory to verify this possibility. In the same way, we used large vortex structure eight line probe measurements and also verified the results of the flow movement displays<sup>(4)</sup>. In conjunction with that, we used a wall surface or skin heat membrane monitoring array along the direction of development to detect a very great drop in the occurrence of pulsations. This speaks clearly of a definite restraining of low speed belts. In this way, turbulent flow energy production trends must have dropped, which is advantageous for drag reduction.

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On the basis of the mechanisms above, we put forward a type of effective improvement to the current systems' methods, that is, moving type plate control devices. Fig.3 is the drag reduction characteristics before and after reciprocating type moving plate control devices or manipulators. Due to plate movements back and forth, the drag forces from the system itself are reduced. Moreover, the scope of plate fixed wall effects is expanded. Because of this, they possess even better drag reduction results. For example, using chord length  $l = 0.93 \delta$ ,  $R = 0.7 \delta$ , single plates with reciprocating motion frequencies of  $f = 5$  Hz achieved

net drag reduction benefits of 7.6%. This verifies a step further that flat plate fixed wall inhibition of hairpin structures is a principal mechanism in drag reduction.

### III. RECENT DEVELOPMENTS

The most recent developments in plate type turbulent flow control devices show that, in combination with such areas as other drag reduction methods, if one combines them with conditions to control large vortex sonic shock and fits them together with wall surface trough pattern methods, etc. these are all new realms awaiting more detailed investigations. Indeed, the great majority of current experimentation is all carried out in laboratories with relatively good environments. Other influences are relatively small. However, even if this type of system, in a situation where there is a smooth pressure, back pressure gradient, has relatively large background turbulent flow involvement, and so on, even with interference, one still gets excellent displays. Because of this, it possesses very strong practical applications. Once optimized designs are realized, it will then be possible to fit them onto currently existing aircraft creating the economic benefits of energy savings and increased speeds. Plate control devices or manipulators, in another arena, are used in the control of flow movements within round tubes. However, up to now, net drag reduction benefits have still not been obtained. This awaits further research.

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